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Verification of a plasma photonic crystal for microwaves of millimeter wavelength range using two-dimensional array of columnar microplasmas

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We experimentally verified that a microplasma assembly can create a functional dielectric layer for the propagation of electromagnetic waves as a "plasma photonic crystal." A two-dimensional array in a square lattice was composed of columnar plasmas of about 2 mm in diameter, and the transmitted microwaves at 70–75 GHz showed a change of energy flow direction. This result is attributed to the fact that periodical structure is composed of individual plasma columns with a different dispersion than the ambient part and the experimental frequency range lies in the vicinity of the lowest band gap of the photonic crystal calculated theoretically. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2147709]

When a plasma becomes much smaller than a given system scale and the production position of an individual plasma is controllable, such small (or micro) plasmas can be converted into a functional assembly. Their collective effects potentially give rise to novel aspects of plasma science and technology. Here, we propose a "plasma photonic crystal," that is, periodical two- (or three-) dimensional structure of spatially- and dynamically controlled microplasmas that plays a significant role in changing the refraction of electromagnetic waves. In "normal" photonic crystals composed of solid materials including dielectrics and metals, such unique characteristics as band gaps and negative refraction, which cannot be accomplished in bulk materials, have been demonstrated.[1,2] By replacing solid materials with plasmas, two important features are added to usual photonic crystals: dynamical (time-varying) controllability and strong dispersion around the electron plasma frequency.[3] These facts will lead to the development of dynamic and functional devices to electromagnetic waves ranging from microwaves to THz waves, according to the scale and the electron density of such plasmas.

In this brief letter, we demonstrate the experimental results on photonic band gap in a two-dimensional plasma photonic crystal that was proposed in our previous work.[4,5] Using a square lattice of columnar atmospheric He plasmas, the transmittance of millimeter waves at 70–75 GHz is examined, and the change of wave energy flow is observed. Band diagrams of plasma photonic crystals composed of collisional plasma columns are calculated from a plane-wave expansion method with equivalent dielectric coefficients to electron density n_e. The obtained band diagram indicates the existence of a unidirectional photonic band gap in the Γ-X direction, which is consistent with the observed frequency range of the unusual wave energy flow.

The production of long-channel He plasmas at atmospheric pressure was reported in our previous report,[6] which is briefly reviewed in Fig. 1. Microdischarges were generated in coaxial dielectric-barrier structures in the aligned holes of metal electrodes. The third electrode was set apart 6 mm from the integrated-microdischarge plane, and extended discharges took place toward the electrode and formed plasma columns, where they were ignited in the presence of initial electrons supplied by the microdischarges. In the experiment reported here, positive square pulse voltage was applied to the third electrode to increase the multiplication factor of the electrons, whereas in our previous experiment the third electrode was on the grounded level.[6] The time evolutions of the

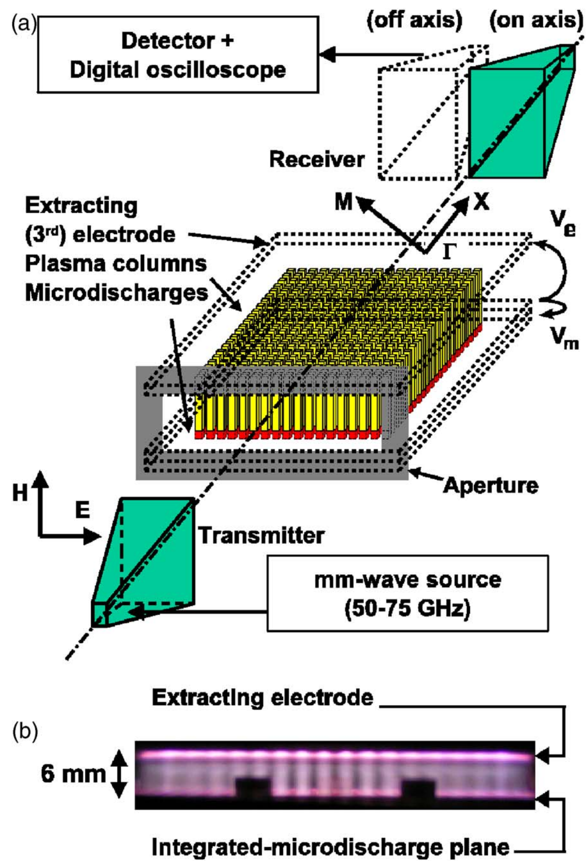

FIG. 1. (Color online) (a) Schematic view of a plasma photonic crystal in our experimental setup. The periodical two-dimensional structure has an area of 44 mm×44 mm. The metal aperture prevents electromagnetic waves from entering the photonic crystal region along other paths. The distance between the plasma photonic crystal and the transmitter or the receiver is 80 mm. Horn antennas are set to realize TE-mode propagation. (b) Visible emission of the plasma photonic crystal.

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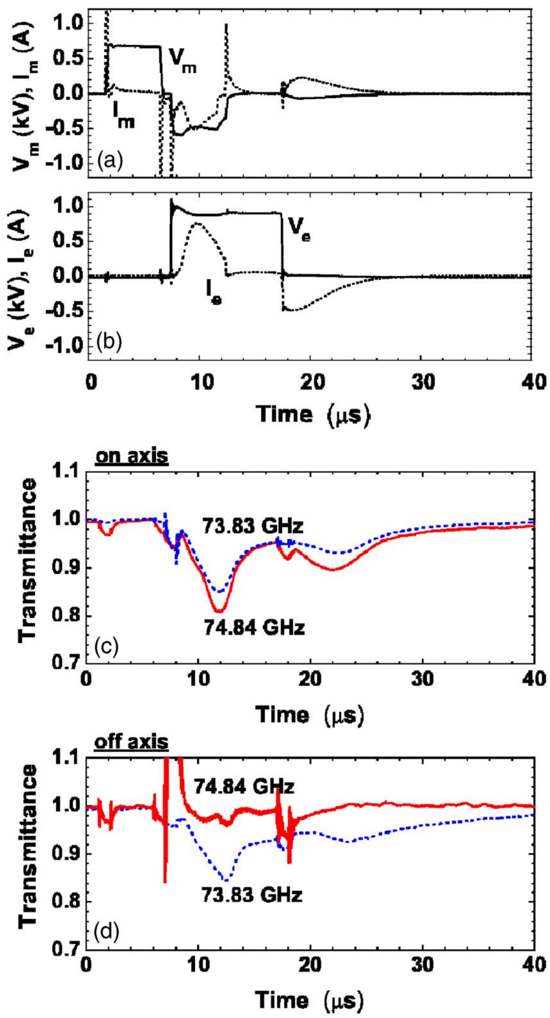

FIG. 2. (Color online) Time evolutions of transmittance signals at different detection positions with discharge signals. Applied voltage and current signals of (a) V_m with I_m and (b) V_e with I_e. (c) Transmittance signals at on-axis detection position at two different frequencies. (d) Transmittance signals at off-axis detection position at two different frequencies.

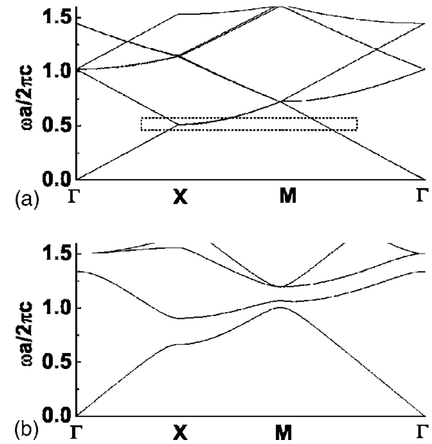

FIG. 3. Band diagrams of plasma photonic crystals of circular-shaped columns in a square lattice, calculated from plane-wave expansion method, where c is the speed of light. Dielectric coefficients of collisional plasmas are derived from (a) $n_e = 5\times10^{12}$ cm^{-3} and (b) $n_e = 5\times10^{13}$ cm^{-3}. The area enclosed by the inset dotted lines indicates the enlarged region in Fig. 4(b).

discharge signals are displayed in Figs. 2(a) and 2(b), and the corresponding visible emission patterns are shown in Fig. 1(b). The columnar plasmas, which were active during the discharge currents and lasted for several microseconds,[7] formed a temporal two-dimensional structure in a square lattice on the microdischarge-integrated plane, where lattice constant a was 2.1 mm. Since a microdischarge was generated in a square hole with opening of 1.4 mm × 1.4 mm, the corresponding extended discharge maintained almost the same cross section or turned into slightly circular columns due to radial diffusion of the plasma particles, verified by the visible emission pattern shown in Fig. 1(b).

The electromagnetic waves were excited at a millimeter wave source (83624B and 83557A, Agilent Technology) at 50–75 GHz and launched from a usual pyramidal horn antenna (SGH-15, millitech). Through a vacuum window they entered the aperture adjacent to the plasma photonic crystal. On the other side of the plasma photonic crystal, through a vacuum window again, a pyramidal horn antenna (SGH-15) receiver was located. The propagation mode of the electromagnetic wave is determined by the angle of the pyramidal horn antennas, where the electric field is parallel to the shorter side and the magnetic field is perpendicular to the electric field. In the following experiment, millimeter waves were excited at the transverse electric (TE) (in-plane electric field) mode. Since there is a certain distance (80 mm) between the plasma photonic crystal and the receiver, what we observed was electromagnetic wave propagation in the far-field region.

Figure 2 displays the electromagnetic wave signals with discharge voltage and currents. The bipolar voltage pulses V_m generated integrated microdischages with total current I_m. When positive voltage pulse V_e was applied to the third electrode, large discharge current I_e flew between the microdischarges and the third electrode followed by extended discharges, and the detected transmittance signals changed drastically. Here "on-axis" detection indicates that the midpoint of the receiver aperture is located on the symmetrical axis of the transmitter antenna, and "off-axis" detection indicates that the receiver axis is located 14 mm apart from the axis of the transmitter. At the microwave frequency $\omega/2\pi = 73.83$ GHz, transmittance decreased with discharge current by 10–20% due to wave damping in collisional plasmas, and it does not depend on the detection positions. On the other hand, at 74.84 GHz, the signals were quite different at the two detection positions. In on-axis measurements, transmittance reduction was larger than at 73.83 GHz, whereas the transmittance signal showed almost no reduction in off-axis measurements. As mentioned earlier, wave energy definitely decreases through plasmas, and so a condition without reduction is possible by additional energy influx that otherwise flows in a different direction.

The nature of the observed wave energy flow can be understood from the dispersion characteristics of the plasma photonic crystals. Band diagrams of the TE mode in a square lattice of plasma columns are displayed in Fig. 3. These calculations are based on the plane-wave expansion method developed for the derivation of usual photonic crystal band diagrams, and the relative dielectric constant is assumed to be $\varepsilon_r = 1 - \omega_{\mathrm{pe}}^2/\nu_{\mathrm{m}}^2$ in the limit of $\nu_{\mathrm{m}} \gg \omega$, and the equivalent radius of plasma columns is set to be $r = 0.87$ mm. Here, ω_{pe} is the electron plasma frequency, and ν_{m} is the elastic collision frequency based on elastic collision cross section,[8] gas pressure, and electron thermal velocity, and was set at 450 GHz. More rigorously, ε_r is a function of both ω and n_e,

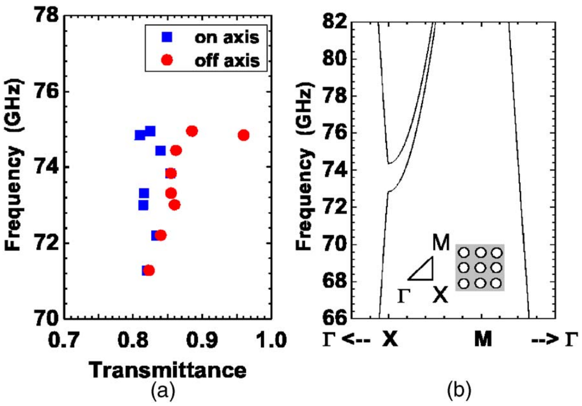

FIG. 4. (Color online) (a) Transmittance signals as a function of frequency. Closed squares and circles show on-axis and off-axis measurements, respectively. (b) Band diagram enlarged from the marked area in Fig. 3(a).

leading to abnormal dispersion around $\omega = \omega_{pe}$.[5] The approximation applied here is valid to obtain an overview of a band diagram and to analyze the narrow frequency range near the photonic band gap. With increasing n_e, shown in Fig. 3(b), ε_r separates from the background relative dielectric constant (=1), and periodical structure significantly affects the band diagrams.

Figure 4(a) shows observed transmittance as a function of frequency, and Fig. 4(b) displays the enlarged theoretical band diagram from Fig. 3(a), which indicates that the unidirectional band gap along Γ-*X* exists from 73.0 to 74.5 GHz. These frequency range values will change when the assumed n_e is varied, as shown in Fig. 3. The detected signals by on-axis measurement show almost no significant change or only slight decrease near 75 GHz. On the other hand, the results of off-axis measurement shows increase of transmittance with increasing frequency and a rapid jump in the vicinity of 75 GHz, which means that the wave energy changes its flow path to the Γ-*M* direction that is predicted in Fig. 4(b). The ambiguity of these results depends on low spatial resolution due to the finite size of the aperture of the pyramidal horn antenna. Additional increase of n_e will enlarge the photonic band gap in this plasma assembly applicable to a dynamic filter for millimeter waves.

In summary, we demonstrated the experimental verification of photonic band gap in two-dimensional plasma photonic crystals. Periodical two-dimensional structure was created using atmospheric He columnar plasmas, and the propagation direction of the electromagnetic waves was significantly deformed. The condition of this anomalous propagation resembled the lowest photonic band gap in a theoretical band diagram with collisional plasma dispersion.

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